High Sensitive Multi Sensor and Analysis Systems for Condition Monitoring and Fault Diagnosis at Gears

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Abstract. Modern high performance transmissions in fabrication and energy industries more and more have to satisfy high requirements concerning their nominal load, running properties and operational stability. Helical gears with small modules are usually used to meet these demands. To assure an undisturbed operation, to avoid unplanned downtimes and consequential damages of high performance transmissions a condition monitoring and fault diagnosis is useful.

The running properties, rate of wear and the development of damages of precision forged and conventional helical gear wheels are analyzed at the IW in a special transmission test bench. The condition monitoring of the test bench is done by vibration and acoustic emission measurements which allow the actual description of the running properties and the development of damages. For the early detection of damages like pitting or cracks at the tooth root, analysis techniques in time and frequency domain and the wavelet analysis have been adapted. Because of the higher resolution in the time domain the wavelet analysis is more suitable for the analysis of frequency components caused by very short excitations, like the beginning of pitting and the propagation of cracks, than the Fast Fourier Transformation. Characteristic values in time and frequency domain (statistical time values, teeth mesh frequencies, cepstral values) are used for the development of a vector analysis to classify different faults. These characteristic values build up a multidimensional vector of the actual running condition which is compared to the vector of the reference condition. This analysis method allows a very early fault diagnosis and an estimation of the operational time remaining.

The detection of cracks in the teeth of gear wheels by vibration analysis is possible with a quite small forecast lead time only. Therefore an eddy current probe has been developed which is located directly at the gear wheel. It can detect volumetric faults like the beginning of pitting or crack initiations in a very early stage during operation.

1. Process Chain for the Production of Precision Forged High Performance Components

Due to the increasing competition, companies are forced to introduce innovative production technologies rather than only relying on the evolution of established processes. The striving for economic production methods with short processing times as well as the risen requirements for properties of today's high performance components moves near-net-shape forming methods into the centre of attention. The goal of the Collaborative Research Centre 489 (SFB 489) is to develop new technological and logistical innovative as well as economic process chains, based on precision forging technology for the mass production of high performance components. One main target is to realize a considerable reduction of the entire process chain which is founded on the integration of manufacturing steps as well as the
substitution of metal cutting sequences by the employment of the precision forging technique. Thus, it is necessary to convert smooth metal cutting sequences for the precision forging process together with an integrated heat treatment. In the same time the solution of the interface adoption between the different manufacturing processes from the domains forming, material science, machining and logistic is necessary. To achieve these goals all aspects of the process chain have to be taken into account. Therefore, the SFB 489 encircles 13 sectional projects, following the production process of the component in the three project domains technology, process chain and logistic.

2. Dynamic load test of components in the Process Chain "Precision Forging"

The high claims at technological properties of the precision forged components like gear wheels require tests at realistic operating conditions. Hence one central point of the project is fixed by the Diagnosis of Components where the precision forged gear wheels are tested in the gear test bench to analyze the running behaviour and the development of damages. In addition to the running and sound behaviour the rate of wear and the development of damages have to be acquired and described by adapted measurement of acceleration and improved analysis techniques (figure 1).

Another point is the out-of-phase determination of quality features dependent on the loading state - like the tooth flank strength and the tooth root strength of precision forged gears - which is essential for the optimization of the components properties and the manufacturing steps in the processing line. Other factors of influence given by the manufacturing process are the surface finish, deviation of tolerances, the reshaped material itself, and the hardening process. The precision forged components are compared with conventional machined components to characterize the influences of the heat treatment and the hard finishing on the qualities and the properties. Long-duration tests at rotation speeds between 1000 and 6000 rpm (depending on the geometry of the test wheel) permit investigations of the fatigue strength against pitting and additionally the analysis of tooth root strength, the crack formation via the crack propagation to the fracture of a tooth. This enables the other sectional projects to optimize the component and the individual process steps.

The condition monitoring of the test bench is done by vibration and acceleration measurements which allow the actual description of signatures of the running behaviour, qualitative and quantitative assessment of wear and the development of damages by appropriate analysis techniques in time and frequency domain.

During the operation of the test bench it was stated that the detection of cracks at the tooth root - especially the crack formation - is possible with restrictions only. Therefore the suitability of acoustic emission analysis was tested and additionally a special sensor for the eddy current crack detection at the rotating gear was applied [7].
2.1 Condition monitoring of the test bench using vibration measurements

State of technology in vibration monitoring of rotating machinery is related to the calculation of standard deviation and/or maximum values, their comparison with thresholds and their trend behaviour to determine increased wear or changes in the operation conditions. Spectrum analysis with special phase constant averaging routines allows to determine machine specific signatures by magnitude and phase relation. By correlation analysis common information of different vibration signals is evaluated for source localization, and cepstrum analysis is used to quantify periodical information of spectral data [1].

A general overview about exemplarily processed statistical time values dependent on the shape of the vibration signal is visualized in Figure 2. Aim of these values is to quantify the visual impression of the time signals as demonstrated here for local and distributed faults. Based on the large statistical variation width in the pure maximum value an integral description of the dynamical signal information is given by the effective value also called standard deviation (STD), squared the variance presents the dynamic signal energy. The Crest-factor describes the peak intensity in the signal progress, calculated by the relation of the maximum value to the root mean square value (RMS).

Through the fourfold exponential weighting of short-time pulse excitation against the energy contained in the signal, the Kurtosis-factor (β) is quite load independent, in contrast to the characteristic values described above. By definition the Kurtosis-factor reaches for purely sinusoidal excitation a value of 1.5 (e.g. pure unbalance excitation), in gaussian noise a value of 3.0 (e.g. stochastical mechanical/flow friction), while for short time pulses within the time set (e.g. short time rubbing, local rolling element bearing damage, cavitation) values up to 100 can appear.

The form-factor, as ratio of the quadratic average (RMS, root mean square value) to the linear average, applies as an analysis tool to share harmonics from coupled information in the signal, with a value of 1.11 for purely harmonical signal components. Stepping up additional damage specific non-harmonical related signal components in the observation period,
or the harmonically components shift themselves, this reflects as changes of the form factor. The single calculation algorithms are to be taken from special literature [9].

To the premature determination of faults and damages of single machine components, the trend setting of certain statistical time values of the vibration signals suits itself. So the initiating and growing of defects in rolling element bearings of pumps, compressors, and drive units in most cases are clearly detected by using statistical time values.

Due to the regarded results the first impression might lead to conclude that time domain analysis by trend setting of statistical values is sufficient to determine faults successfully. Near problems with source localization in complex machinery, the signatures of gear faults are very similar to the ones of bearing faults and superimposed structure resonances often influence the pure time signal analysis.

The single frequency components contained in the time signals can only be determined by amplitude and phase relations of frequency analysis using spectra, coherences and cepstra. To the use of automated routines for failure determination and diagnostic purposes the occurring data quantities have to be reduced to single values as the amplitudes of characteristic frequency components, like the narrow banded spectra information of rotational related excitation as unbalance, misalignment, gear mesh, etc.
The cepstrum, the inverse FFT of the logarithmic spectrum, summarizes all periodical information within one value, e.g. the amplitude and frequency modulations of bearing, gear, and blade faults become visible at increased amplitudes of the speed harmonics. If faults at rotational speed related machine components occur, these modulations are visible at these harmonics. The combination of excited center frequency, for the fault example the teeth mesh (TM), and the cepstrum amplitudes (Cn) at the 1st speed harmonic characterize the fault in Figure 3.

Broad banded information of system and fluid resonances are monitored by FFT-integrals in certain frequency ranges. Friction related information is represented in the spectra ground level ($\Delta \log$). Multi sensor systems in combination with correlation techniques avoid measurement errors and determine excitation sources. Similar to the cepstrum analysis the holecence (inverse FFT of the coherence) enables to summarize all periodically related information obtained in two signals.

Therefore a distributed fault at a gear wheel can be identified by supervision of specific frequency related components. This is the teeth mesh (TM) frequency whose amplitude will go down whereas additional sidebands to the teeth mesh frequency appear in the distance of the rotational speed ($n$) which is also visible in the cepstrum at the speed quefrency. Another symptom is the rise of the signal ground level because of the additional friction components because of the propagating fault [10].

### 2.2 Determination of fault patterns and their classification

In order to detect all known failure mechanisms and their effects to the characteristic values a further step is the calculation of vectors. Simplified a matrix of single values, e.g. the statistical time values, certain machine specific frequency components (e.g. teeth mesh, rotational speed, etc.), and the corresponding cepstrum components like shown in the figure 4.

A cross-link with a weighting function can emphasize certain fault patterns. The premise of
an automatic damage analysis is the relation to a fault free reference condition. Therefore a sufficient number of independent measured values are necessary to build a reference class. The greater the number of references the better are the statistical values. Changes in the operational behaviour become directly visible and experienced operational staff is able to determine different classes of defect. Related to complex machinery the information has to be compressed further, here several single components interact and the obtained information is not only related to one sensor signal.

According to the type of defect, the vectors produce the largest correlation for failure and grade of damage. The distance and angle between the vectors present an easy classification and consider the correlation between the measuring vectors and the prototype or reference vector. The simplest type of classification is reached by the minimal analysis of distance, magnitude and angle between each of them. As result an actual condition based classification of the actual machine’s condition is obtained. Certain more complex algorithms for classification have to be applied, if the single failure classes are not clearly separated. This principle of signal classification is also used in the field of eddy current measurements for failure detection and material classification, ultrasonic testing or automatic image processing of x-ray inspection.

The signal classes for tooth fracture and pitting in figure 5 can be easily distinguished. And even the beginning of local pitting can easily be distinguished from the reference area. But the measurements have obtained too, that due to interference of other damage signatures, when using vibration measurement only, the damage areas can be moved. Using a rating vector the distance between the different classes can be increased.

Another point in figure 5 is the detection of a crack. The vector for a crack is not clearly out of the reference area. A crack can be detected by vibration measurements and conventional analysis methods like the FFT only when the teeth mesh is already much disturbed. Therefore an analysis method which is more sensitive to short excitations than the FFT has to be implemented, like the wavelet analysis.
3. Wavelet analysis of different faults

As a new analysis technique to determine fault patterns the Wavelet analysis provides a method of decomposing a recorded signal into a family of component parts. For general signal analysis, the objective is usually to extract frequency data from the signal and learn how its frequency composition changes with time. The wavelet method provides a good means of doing this because each wavelet has a particular frequency content and is located at a particular position on the time axis. There are many ways of choosing the form of the analyzing wavelet. The theory is quite complicated. In general this analysis method could be looked at as a type of filtering signal information by certain window functions to emphasize occurring high frequent and low frequent excitation with the same amplification to determine even lowest signal intensities in the analyzed signals, even if they only arise for a short time [3].

3.1 Wavelet analysis of propagating crack

The development of different faults like pitting and fracture of teeth is described in the following wavelet transformations using the Gabor wavelet [2]. Used are the time signals of an accelerometer located at the gearbox. In the upper part of the figures the time signal is visible whereas in the lower part is the wavelet transformation, both displayed for 6 revolutions. The x-axis represents the time in microseconds, the y-axis the frequency and the intensities are shown by a colour scheme. Figure 6 shows the undisturbed reference condition of a helical gear wheel at about 620,000 load cycles.

At a frequency of 1665 Hz the teeth mesh frequency is clearly visible. The intensity should be continuous like for the first two revolutions. During the next revolutions slight differences can be seen. The second harmonic of the teeth mesh frequency at 3330 Hz is visible too, but only with low intensities. In the frequency area above 2000 Hz every teeth mesh leads to an intensity change in the wavelets. So each teeth mesh is clearly visible as 37 intensity rises over one revolution.
Figure 6: Wavelet of reference condition, 620,000 load cycles

Figure 7: Wavelet of crack, 3,900,000 load cycles
About 3 million load cycles later at 3,900,000 load cycles figure 7 shows the behaviour with a crack. The crack is already in a state that the teeth mesh is disturbed by the bending of the cracked tooth, the contact ratio becomes less. At the teeth mesh frequency (1665 Hz) the 6 revolutions are clearly visible as a periodic rise of intensities. The second harmonic of
the teeth mesh frequency (3330 Hz) shows periodic signal peaks too. But there is also a low frequent component at 600 Hz which becomes visible, and could not be seen at the reference condition. Looking at the time signals only just slight differences can be seen. Only a few load cycles later at 4,050,000 load cycles (figure 8) the crack has propagated that far, that the cracked tooth is not bearing load anymore and the next tooth gets its load with a shock pulse, which leads to a crack initiation at that tooth, too. This is clearly visible in the time signals and the wavelet transformations by high intensities at the second harmonic of the teeth mesh frequency (3330 Hz). This leads to an excitation of the teeth mesh frequency (1650 Hz) and the lower component at 600 Hz.

In the next figure 9 about 25,000 load cycles later at 4,075,000 load cycles the cracked tooth has gone and even the second tooth which had a crack initiation before has broken away. Now there are even greater shock excitations with amplitudes up to 500 m/s². The detection of a crack via analysis of vibration signals is possible but only with a very short forecast lead time of 100,000 load cycles which equals 0.5 hours at the test bench.

3.2 Wavelet analysis of propagating pitting

With the intention to compare the running properties of conventionally grinded and precision forged gear wheels an amount of 50 gear wheels were manufactured conventionally by a gear wheel manufacturer. Before testing these gear wheels in the transmission test bench to analyze the running properties non-destructive determination of surface hardness of single teeth have been performed. The results of these measurements showed a significant difference in single teeth hardness over the circumference at one batch gear wheels. Only one side of the gear wheel was hardened, the other side was still soft. Therefore these teeth were prone to pitting.

Figure 10: Wavelet of beginning of pitting, 560,000 load cycles

Figure 10: Wavelet of beginning of pitting, 560,000 load cycles
Pitting at the teeth flanks can be detected much earlier than a crack. Figure 10 shows the beginning of pitting at a faulty hardened conventional gear wheel. Clearly visible are locally high intensities at the second harmonic of the teeth mesh frequency of 3330 Hz. About 1 million load cycles later at 1,400,000 load cycles the local pitting becomes more
distinct by high intensities at the teeth mesh frequency (1650 Hz) combined with low intensities at the second harmonic of the teeth mesh frequency at the same time (figure 11). Spreaded pitting is visible in figure 12 which shows the operating conditions 400,000 load cycles later. High intensities can now be seen at the teeth mesh frequency and its second harmonic leading to a distributed fault. Now the fault is visible in the time signal too. Additionally signal parts at about 600 Hz appear due to the worse contact ratio because of deformation of the teeth and initiated cracks at the tooth roots. The test bench was shut down afterwards.

4. Detection of gear faults with acoustic emission analysis

Since the conventional vibration measurements detects a crack at the tooth root not before the teeth mesh is already disturbed some measurement principles have been tested for their qualification to detect cracks at an earlier stage. A good means for the detection and localization of cracks at tanks, pressure vessels and static structures is the acoustic emission analysis [8]. Acoustic emission measurement techniques have also been used for pitting detection at test benches [5,6]. Therefore the crack detection with acoustic emission sensors was tested at the gear test bench.

Acoustic emission sensors show a quite different behaviour than accelerometers. Accelerometers have a linear working range lower than their resonance frequency up to 180 kHz. They show a signal dependent on the vibration of the mounting surface. Acoustic emission sensors are highly sensitive in their resonance ranges from ca. 50 kHz up to 2 MHz.
Whereas accelerometers detect the vibration of the measurement position or component itself, an acoustic emission sensor is much more sensitive at higher frequencies to detect acoustic emissions born by cracks, dislocations or corrosion. In addition to the instrumentation with accelerometers one of the gearboxes was equipped with acoustic emission sensors at different measurement positions. The different sensor positions were chosen because of their signal paths. Two acoustic emission sensors were placed on the two bearing housings, fixed bearing and loose bearing. One is placed on the lubrication conduit and another one right in the oil beam of the oil conduit, to get acoustic emissions which may cause a feedback via the oil beam. The coupling of sensors using a beam of liquid or lubrication has already been successfully conceived in tribological tests regarding slip rolling friction [4]. Last but not least a rotating acoustic emission sensor is placed at the end of the shaft with the test gear. The sensor itself is positioned at the rotating end of the shaft, containing a sender which is facing a receiver and sending the acoustic emission information via induction.

For data acquisition a multi channel acoustic emission measurement system was used using statistical methods to investigate acoustic emission properties like amplitude, energy, hits and counts. Additionally the sensor signals were periodically obtained by a high frequent transient measurement system to get transient data of several revolutions of the test shaft.

![AE-data of reference condition and defect, rotating sensor](image)

During first test measurements with different speeds and different loads the influences of these parameters on the signal to noise ratio were identified and the thresholds for the acoustic emission amplitudes were set. The variation of the rotational speed of the test shaft showed that at speeds above 25Hz the overall signal levels was higher than the anticipated
impulse levels for gear wheel faults. This high level of acoustic emissions is supposed to be caused by the rise of dynamic influences of the roller bearings and teeth mesh. Therefore the test for the detection of faults and their initiation were conducted with a maximum rotational speed of 25Hz. Usually the test bench operates with a rotational speed of 45Hz. At this speed different loads from 200 to 450Nm showed no significant influences. For the following description of the fault initiation and propagation only the information of the rotating acoustic emission sensor at the end of the test shaft is used. The other sensors showed no significant information about the condition of the test wheel because of their complex signal path. Fig. 13 shows the arrangement of the different sensors and the transmission path from the teeth to the sensor. A mounting of an acoustic emission sensor directly at the gearwheel was not possible because of the shape and size of the gear wheel and the dimensions of the gear box. Additionally the connection of signal cables to a sensor directly at the wheel via the rotating shaft is quite difficult.

After the mounting of a test wheel and start-up of the test bench during the first hours of operation a quite high amount of acoustic emissions can be detected. These acoustic emissions are caused by seizing of the keys and contact areas of the test gear and the shaft. After a few hours this run-in effect is over and the normal operation condition with only a very small amount of events is reached.

Figure 14 shows the progression of acoustic emission signal properties for the undisturbed reference condition after run in and the crack initiation and propagation until the failure of the gear wheel and shut down of the test bench. For the description of the acoustic emission signals the number of hits and the energy of the signals are shown which are usually used for failure detection. In the upper part the number of hits during the reference condition is very low, whereas in the lower part of figure 14 the crack initiation can be detected by an increasing hit rate caused by the opening and closing of the crack during one revolution of the test wheel. In this case the energy of the AE-signals shown for the two conditions shows no significant changes regarding the fracture of a tooth of the gear wheel. The detection of cracks at the tooth root via acoustic emission analysis is possible but it is restricted to a maximum rotational speed of 25Hz instead of 45Hz in this case since the overall signal level becomes higher than the acoustic emissions of the defect because of additional dynamic influences of teeth mesh and roller bearings.

5. Crack detection at gear wheels with an eddy current sensor

Using the condition monitoring of vibration signals the forecast lead time of fracture of a tooth is very small only. Detection is possible when the crack has propagated so far that a disturbance of the teeth mesh occurs and the contact ratio gets less. To increase the forecast lead time and to detect the first crack initiation an eddy current crack detection was developed additionally [1].

The first approach was to use two sensors which were arranged at the face side of the gear wheel to detect cracks that are initiated at the side of the gear wheel. But cracks can be initiated not only from the sides of the teeth. A crack initiation may occur from the middle of the teeth too or can be initiated by a pitting on the tooth flank. To detect this too, an eddy current sensor was developed which scans the whole tooth and has a measurement range to reach even the tooth root. Figure 15 shows the signals of different faults. With this new eddy current sensor a very early detection of tooth faults is possible. Displayed are different faults and the signal of a new gear wheel. Each fault shows great changes in the amplitude of the sensors signal, therefore no additional analysis algorithms are necessary. Not only cracks, also pitting, every fault which changes the volumetric behaviour of teeth can be
detected in an early stage. With this arrangement a forecast lead time of 400,000 load cycles or 2.5 hours is possible at the test bench for this case.

![Diagram showing eddy current detection of volumetric faults](image)

**Figure 15: Eddy current detection of volumetric faults**

6. **Summary**

To value the properties of the precision forged gear wheels, like running behaviour, tooth flank strength and tooth root strength, after the finishing process a test under real conditions compared with conventional machined components is necessary. The condition monitoring of the test bench is done by vibration measurements which allow the actual description of the running properties and the development of damages by appropriate analysis techniques in time, frequency and time-frequency domain. Therefore slowly arising faults like pitting can be recognized very early. The detection of cracks at the tooth root, especially the crack formation, is possible with restrictions only.

The analysis of acoustic emission data allows an earlier detection of a crack development because of the opening and closing of the crack during one revolution of the test wheel before the teeth mesh is disturbed. But this technique is restricted to a maximum rotational speed of 25Hz instead of 45Hz in this case since the overall signal level becomes higher than the acoustic emissions of the defect because of additional dynamic influences of teeth mesh and roller bearings.

Additionally an eddy current sensor for crack detection at the rotating gear is applied. With conventional methods, like the FFT of vibration signals, the forecast lead time of a fracture is quite short. With the wavelet analysis of vibration signals a fracture can be detected as
soon as the teeth mesh is disturbed, about 200,000 load cycles before failure, which equals 1.25 hours at the test bench. The earliest detection of teeth faults is possible with the eddy current sensor which has a change in its signal when a volumetric fault like a crack or pitting is initiated. At the test bench there is a forecast lead time of 400,000 load cycles, which equals 2.5 hours.

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8. References